How can we live within the safe and just Earth system boundaries for blue water?

Ben Stewart-Koster (b.stewart-koster@griffith.edu.au)
Griffith University https://orcid.org/0000-0001-8334-0825

Stuart Bunn
Griffith University https://orcid.org/0000-0002-6540-3586

Pamela Green
City University New York

Christopher Ndehedehe
Griffith University https://orcid.org/0000-0003-1906-9764

Lauren Andersen
PIK https://orcid.org/0000-0003-3080-0503

David Armstrong McKay
Global Systems Institute, University of Exeter

Xuemei Bai
Australian National University https://orcid.org/0000-0001-6556-8041

Fabrice DeClerck
Alliance of Bioversity International & CIAT https://orcid.org/0000-0002-3631-8745

Kristie Ebi
University of Washington https://orcid.org/0000-0003-4746-8236

Christopher Gordon
University of Ghana

Joyeeta Gupta
Governance and Inclusive Development, Geography, Planning, and International Development Studies, AISSR, University of Amsterdam https://orcid.org/0000-0003-1424-2660

Syezlin Hasan
Australian Rivers Institute & Griffith Business School https://orcid.org/0000-0002-0637-7963

Lisa Jacobson
Future Earth https://orcid.org/0000-0003-4936-2275

Steven Lade
Future Earth https://orcid.org/0000-0001-9719-9826

Diana Liverman
University of Arizona

Awaz Mohamed
Universitat Hamburg https://orcid.org/0000-0002-6130-9496

Sina Loriani
Potsdam Institute for Climate Impact Research, Member of the Leibniz Association
https://orcid.org/0000-0001-6660-960X
Nebojsa Nakicenovic
International Institute for Applied Systems Analysis and Vienna University of Technology
David Obura
CORDIO East Africa https://orcid.org/0000-0003-2256-6649
Dahe Qin
State Key Laboratory of Cryospheric Sciences, CAS
Crelis Rammelt
Amsterdam Institute for Social Science Research, University of Amsterdam https://orcid.org/0000-0002-3766-2599
Juan Rocha
Stockholm Resilience Centre, Stockholm University; Future Earth Global Hub Sweden
Johan Rockström
Potsdam Institute for Climate Impact Research https://orcid.org/0000-0001-8988-2983
Peter Verburg
Institute for Environmental Studies (IVM), Vrije Universiteit Amsterdam https://orcid.org/0000-0002-6977-7104
Caroline Zimm
IIASA https://orcid.org/0000-0001-5603-1015

Article

Keywords:

Posted Date: May 2nd, 2023

DOI: https://doi.org/10.21203/rs.3.rs-2861426/v1

Additional Declarations: There is **NO** Competing Interest.

Version of Record: A version of this preprint was published at Nature Sustainability on November 16th, 2023. See the published version at https://doi.org/10.1038/s41893-023-01247-w.

Abstract

Safe and just Earth System Boundaries (ESBs) for surface and groundwater (blue water) have been defined for sustainable water management in the Anthropocene. We evaluate where minimum human needs can be met within the surface water ESB and, where this is not possible, identify how much groundwater is required. 2.6 billion people live in catchments where groundwater is needed because they are already outside the surface water ESB or have insufficient surface water to meet human needs and the ESB. Approximately 1.4 billion people live in catchments where demand side transformations are required as they either exceed the surface water ESB or face a decline in groundwater recharge and cannot meet minimum needs within the ESB. A further 1.5 billion people live in catchments outside the ESB with insufficient surface water to meet needs, requiring both supply and demand-side transformations. These results highlight the challenges and opportunities of meeting even basic human access needs to water and protecting aquatic ecosystems.

Main

The global water cycle and in particular, surface and groundwater flows (blue water) have been greatly impacted during the Anthropocene[1,2,3]. Natural blue water flows, to which aquatic biota are historically adapted[4], underpin the health of freshwater ecosystems which, in turn, provide a range of ecosystem services to communities worldwide[5]. Intact catchments contribute hundreds of billions of dollars of value annually towards national water security at the global scale, through the avoided costs of water resource infrastructure and services[6]. Freshwater wetlands provide a range of high-value services, including cleansing polluted water and recharging groundwater aquifers[7], and mangroves are vital for the livelihoods of many coastal communities in the tropics[8]. Inland fisheries, including aquaculture production, which depend on freshwater flows[9] contribute over 40% of the world's capture finfish fisheries[10]. Over 70% of the world's coastal and estuarine fish catch comes from species that rely on freshwater flows to oceans[11].

Alteration of surface water flows has had considerable impact on aquatic and terrestrial ecosystems worldwide[12,13], putting natural systems and their provision of ecosystem services at risk[14]. Over-extraction of groundwater has led to widespread land subsidence, deterioration of groundwater dependent ecosystems, reduced surface water flows and increasing costs of water extraction[15,16,17]. Saltwater intrusion into coastal aquifers[18] and reductions in water quality from groundwater pollution[19] also reduce water availability for domestic and agricultural use. The broad range of biophysical impacts from alterations to blue water flows are often disproportionately felt by vulnerable communities due to the loss of access to water and the ecosystem services it delivers[20,21].

A first attempt to quantify the maximum allowed human alteration of the global hydrological cycle on land, was carried out as part of the Planetary Boundary framework[22,23], defining the global freshwater boundary as the limit of human withdrawals of consumptive blue water use. This was a proxy for the alteration of both green (soil moisture generating evaporation and transpiration flows) and blue water partitioning (safeguarding a minimum level of environmental water flows)[24]. Recently, green water alterations were added to the planetary boundary assessment, concluding that human shifts of soil moisture exceed the maximum range of variability over the recent Holocene, suggesting that green water alterations are today outside of the safe operating space[25]. These shifts in green water flow alter moisture recycling from land, affecting atmospheric rivers and downwind rainfall. As 50% on average of terrestrial rainfall originates from green water flows (the remaining from the ocean), these do impact on future rainfall and blue water flows. The urgency of recognising the fact that humanity is altering the source of all blue and green water - precipitation - through climate change and shifts in moisture recycling, has been recently highlighted[26].

Safe and just Earth System Boundaries (ESBs) for surface and groundwater have recently been proposed[27] to provide guidance on these critical issues, drawing on defined needs for minimum access to water[28] and the principles of Earth system justice[29]. Earth system justice is defined here in terms of intragenerational (between today's countries, communities and individuals), intergenerational (between past, present and future generations) and interspecies (between people and nature) and includes both distributional and procedural justice[29]. In this context, the safe and just ESBs for blue water have been defined to protect aquatic ecosystems and the services they provide[27]. Flow-ecology research has identified the importance of critical components of the natural flow regime, including the timing, magnitude, duration, frequency and rate of change of key flow events[30]. The general findings from this research have been used to define the safe and just ESBs for surface water at the catchment scale as ± 20% alteration of monthly flows, leaving 80% of monthly flows for the environment[27,31]. The safe and just ESB for groundwater was defined as an average annual drawdown no greater than average annual recharge to ensure there was no decline in aquifer depth[27]. These sub-global ESBs have been defined for individual catchments and aquifers, and to meet them at the global-scale requires 100% of all land surface areas within the catchment-scale boundaries to be within the safe and just ESBs.

The framework of ESBs can be used to operationalize and quantify intragenerational justice in terms of preventing exposure of people to significant harm[29]. Protecting surface and groundwater systems while providing water for a broad set of human needs represents a considerable challenge for Earth system justice[27,29]. This concern is particularly acute in impoverished and water scarce regions that already face challenges in meeting the basic needs of local populations due to water shortages, poor water quality, highly inequitable access, water being diverted to other uses or a combination of these[32]. These areas are often disproportionately affected by increasing climate variability[33]. In general, providing a minimum level access to resources for all people can be achieved through reduction and reallocations of resource consumption, especially to the most vulnerable and those without access, as well as transformational changes in technology, governance and other key drivers[34].

Defining a minimum access level to water is an inherently fraught but important exercise given the importance of water to survival and wellbeing[35]. Two levels of access to blue water are considered here; a minimum (50 L person^{-1} day^{-1}) required to maintain basic dignity (not just survival) and a slightly higher level (100 L person^{-1} day^{-1}) required to escape from poverty, based on the intermediate and optimal level of access for daily domestic needs, including sanitation, defined by WHO[28,36]. The blue water demand to meet access needs for wellbeing in addition to daily domestic water (including food and energy production, and infrastructure for housing and mobility) increases this to 293 (Level 1) and 406 (Level 2) L person^{-1} day^{-1}. Billions of people do not have access to this basic level of water but many others use much more, with global average water use around 1500 L person^{-1} day^{-1} [28]. Meeting all water requirements for domestic, industry, food (adequate 2,500 kcal/p/day diet) and energy, equally for all would require more than twice this volume but noting this would be derived from a combination of blue and green sources[26]. While not fully addressing all dimensions of justice, defining access for the blue water share of human needs offers a benchmark for comparison in meeting the basic wellbeing of all humans while maintaining a safe Earth system. Meeting at least these access levels for all people while remaining within the safe and just ESBs for blue water is a critical goal to keep all humans within a safe and just corridor[27].

Here we combine global modelled data on surface and groundwater availability, between 2000–2020, with estimated basic human access needs for blue water, for domestic use, food and energy production. Since surface water tends to be the first (and cheapest) source of water appropriated for human needs, we identify where we can and cannot respect the safe and just ESBs on an annual basis if all people have equal access only to the minimum levels of water described above, using modelled unaltered surface water flows from within their respective catchments. We then estimate the proportion of annual groundwater recharge that would be required to provide just access levels where we cannot meet those needs from surface water alone, while respecting the ESB for surface water. We also show where the annual groundwater recharge rate is itself in decline, highlighting how climatic variability (shifting overall vapour flows and generating more extreme events) and land system change (affecting moisture recycling) is amplifying the challenges of staying within the ESBs. Finally, we examine current surface water flows and identify the different types of supply and demand side transformations including redistribution, needed to return to or stay within the ESBs for surface water while meeting human needs. These analyses are conducted at the catchment scale and summarised by continent and at the global scale.

Results

As expected, our results show it is likely to be challenging to provide even basic access to water for all people while meeting the safe and just ESBs for surface water in many regions. We find that there is sufficient surface water availability, based on unmodified flows, to meet water access needs at domestic Level 2 (100 litres person^{-1} day^{-1}) for 88% of the world's population while remaining within the safe and just ESB for surface water (Table 1). However, 2.6 billion people live in catchments with insufficient annual surface water flows to provide Level 2 access for all needs (406 litres person^{-1} day^{-1}) and still remain inside the ESB (Table 1). This group represents one-third of the global population, with the majority living in Asia (1.7 billion). Despite the large number of people living under such circumstances, this only represents 5% of all catchments globally (Table S2).

Table 1
Population in each continent living in catchments where human needs at different access levels cannot be met with surface water alone, while remaining within the safe and just ESBs. Domestic access levels account for personal water use in the home and 'All needs' levels account for household water use as well as blue water required for food and energy production and household infrastructure. Population numbers are in millions and numbers in parentheses show the proportion of the total population globally and within each continent.

Access levels (volume person^{-1} day^{-1})	Global	Africa	Asia	Australia	Europe	North America	South America
Domestic Level 1 (50 L)	699 (0.09)	147 (0.11)	523 (0.11)	< 1 (0.004)	4 (0.01)	21 (0.03)	4 (0.01)
Domestic Level 2 (100 L)	950 (0.12)	204 (0.15)	670 (0.14)	< 1 (0.004)	20 (0.03)	25 (0.04)	31 (0.07)
All needs Level 1 (293 L)	2,329 (0.29)	355 (0.26)	1639 (0.35)	3 (0.15)	161 (0.22)	110 (0.17)	61 (0.14)
All needs Level 2 (406 L)	2,619 (0.33)	409 (0.30)	1723 (0.36)	9 (0.42)	241 (0.33)	167 (0.26)	69 (0.16)

Meeting the safe and just ESB for surface water in regions that are relatively dry or have dense populations (e.g., much of Africa, parts of Asia, and Australia), would create median daily per-capita deficits close to 406 litres based on Level 2 access for all needs (Fig. 1a). In some parts of the world, these deficits could be met from a relatively low proportion of the average annual groundwater recharge, including catchments in Southern Africa (e.g., the Orange and Limpopo basins), where less than 5% of the average annual recharge would be needed (Fig. 1b). However, in many of the drier and more populous regions, for example in eastern China, this may require 50% or more of the average annual groundwater recharge (Fig. 1b). The spatial patterns of current surface water flow alteration and groundwater decline are consistent with these findings (Table S1; Fig. S1).

The average annual groundwater recharge (2003–2016) tends to be highest in equatorial regions (Fig. 2a). Nonetheless, there are regions in higher latitudes with high annual recharge volumes, such as parts of Scandinavia and northern Russia. Adding to the challenges facing drier and populous regions, the regions that also have relatively low volumes of groundwater recharge tend to be those where a higher proportion of the recharge is required to meet the access levels of water, while remaining within the safe and just ESB for surface water (Fig. 1b and Fig. 2a). For example, in central and eastern China up to 100% of the annual groundwater recharge would be required, and parts of the Middle East where recharge volumes are currently much lower, would require 50%.

Compounding these challenges has been a trend of declining groundwater recharge in some regions, leading to a reduction in the local-scale safe and just ESBs for groundwater (hotter colours in Fig. 2b). Some of these declines in groundwater recharge are associated with declining trends in annual rainfall volumes (yellow shading in Fig. 2b; Fig. S2). For example, declines in annual groundwater recharge, from 2003–2016, across the Indian sub-continent of up to 6 million m^3 $year^{-1}$ have occurred in conjunction with declines in rainfall of up to 10 mm $year^{-1}$ (indicated by the yellow over the red pixels of groundwater trend in Fig. 2b). Similarly, large regions of the South American continent have shown declining groundwater recharge associated with declining annual rainfall during this period. This is contrasted with regions where groundwater recharge has been declining without an associated decline in rainfall, such as parts of eastern Europe and central Africa (indicated by red pixels without any yellow shading in Fig. 2b).

We combined the capacity to meet access needs from unaltered surface flows (Fig. 1), the trend in groundwater recharge (Fig. 2b) and the current level of surface flow alteration (Fig. S1a) to classify catchments into eight groups where transformations would be needed to transition back into the safe and just ESB (Fig. 3 and Fig. 4). These categories identify the number of people across the globe and in each continent where various transformations are necessary to meet all needs Level 2 access (406 litres $person^{-1}$ day^{-1}) while meeting the safe and just ESBs for surface and groundwater. While some regions could rely on supply side transformations by substituting a portion of surface water use with groundwater to meet both access needs and safe and just ESBs, others may require substantial demand side transformations.

There are almost 2.4 billion people living in catchments where only relatively modest transformations to water sources would be required (Groups 1 and 3, Fig. 4). These locations have sufficient surface water flows to meet access needs and flow alteration is not currently exceeding the safe and just ESB. These catchments tend to be those with relatively high levels of flow, low levels of income and/or low population densities, such as the Amazon, Congo and Irrawaddy river basins (Fig. 3). The 2.6 billion people in Groups 2 and 5 live in catchments where supply side transformations to shift from surface to groundwater use may provide the means to stay within the surface water ESB (Group 2) or to meet access needs without exceeding the surface water ESB (Group 5; Fig. 4). These include large river basins such as the Paraná, Zambezi and Yangtze, in Group 2 (Fig. 3), as well as smaller rivers in drier parts of the world where the proportion of groundwater required to meet minimum access needs is relatively low, such as the Tana River in Kenya and the Orange River in South Africa (Fig. 1b; Fig. 3). However, employing supply side transformations will be more difficult in Group 5 rivers where the proportion of groundwater required to meet access needs of dense populations and agriculture is relatively high, such as the Yellow and Indus Rivers (Fig. 1b).

There are 1.4 billion people living in catchments where demand side transformations would be needed to meet the safe and just ESB for surface water (Groups 4, and 7; Fig. 4). These include the Mekong and Niger River basins (Fig. 3) that are currently outside the safe and just ESB for surface water, despite having sufficient surface water flows to meet access needs, while groundwater recharge has been declining (Group 4). This also includes catchments that are currently within the surface water ESB but do not have sufficient surface water flows to meet access needs and where groundwater recharge has been declining (Group 7). The remaining 1.5 billion people live in catchments where a mix of transformations will likely be required as there is insufficient surface water to meet access needs and the level of flow alteration is already beyond the ESB for surface water (Groups 6 and 8). Those living in Group 6 catchments, which includes the Yellow and Indus Rivers (Fig. 3), may be able to increase groundwater use as annual recharge has not been declining in recent years. However, groundwater recharge has been declining in Group 8 catchments, which includes the Chao-Phraya River (Fig. 3), likely necessitating more substantive transformations in water use.

Discussion

We have identified the catchments where basic water needs for all people could be met with surface water alone while staying within the safe and just ESB, supporting about two thirds of the world's population. In the catchments where this would not be possible, we showed what proportion of groundwater recharge would be required to meet basic water needs and stay within the surface water ESB. We also showed that many parts of the world currently face declining groundwater recharge, illustrating the challenge of meeting the basic water needs of humans in a changing climate. In synthesising this information with the current level of surface flow alteration (Supplementary Information) we identified where additional demand and/or supply side transformations could be mobilised to meet equal levels of minimum access needs for all humans and stay within the safe and just ESBs.

Demand side transformations could include a transition to less water intensive foods and other exports[37], and improvements in the efficiency of water use within the catchments including reducing leakage in urban water distribution systems, and particularly in agricultural production, which accounts for approximately 70% of flow alterations globally[38]. There is substantial uncertainty in global estimates of irrigation efficiency[39] and observed improvements have not always been accompanied by reductions in water use, indicating that transformative policies, such as progressive pricing on water use, need to be accompanied by suitable regulatory frameworks and improved catchment-scale water accounting[40]. Nonetheless, there are still many opportunities for further improvements in irrigation efficiency around the world but particularly in catchments in south Asia and sub-Saharan Africa[41] that are currently exceeding the surface water ESB. Demand side improvements such as these can also reduce some of the supply side challenges.

Supply side transformations for domestic water supply could include a transition to different sources of water, such as local groundwater, safely treated recycled water or inter-basin transfers from more water abundant catchments (providing the source catchment would remain within the ESBs). Supply side transformations to meet basic food needs could include greater reliance on agricultural use of green water, which is the water that is naturally available in the root zone (noting that the planetary boundary for green water may have already been transgressed[25]), and other sources such as recycled water to reduce alteration of local blue water flows. Of course, these transformations require local decision making, as they all come with economic, environmental, and social costs and risks, such as the increased costs of groundwater pumping and the subsequent risk of overuse of sub-surface waters[42]. Moreover, such changes will have to grapple with existing property rights regimes to water in many parts of the world[43] which allocate water resources to landowners, permit holders and contractual parties but may stand in the way of redistributing water from one use to another, to those without access, and from one user to another. Guaranteeing procedural justice, which highlights the inclusion of all stakeholders, including Indigenous peoples, and consideration of ecosystem needs for interspecies justice[29] in such transformations will be key.

Transforming blue water use among different supplies and needs will very likely require a mix of supply and demand side transformations. In many catchments, supply side transformations to use more groundwater may help meet the surface water ESB, however, in doing this they may risk transgressing the groundwater ESB. The ESB for groundwater does not prescribe a volume of extraction that can occur, only that total annual drawdown should not exceed long-term average annual recharge. This necessitates local-scale monitoring, missing in many regions, to determine levels of extraction, given the groundwater recharge from the previous year. Meeting this boundary should ensure that extraction of groundwater does not further alter surface water flows, a risk in regions where return flows from extraction are low[44] and complements a previously defined presumptive standard for groundwater extraction[45].

In this study, we did not integrate virtual (also termed embodied) blue water flows, which is the movement between locations through the export and import of products derived from and containing blue water[46,47]. Many water-scarce regions obtain food produced in water-abundant regions[48]. Analyses of blue water flows show that around 15–30% of water used in agricultural production is exported to other catchments and countries[49,50,51]. This is very unevenly distributed with a relatively small number of countries and agricultural products accounting for a large proportion of international virtual water trade[50,52]. Although virtual water movement may result in blue and green water savings at the global scale[53,54], it can contribute substantially to the alteration of flows in some parts of the world[55]. Additionally, virtual water flows also come with an economic cost to importing populations[46]. As such, transformations based on virtual water trade to bring a catchment inside the ESBs may not necessarily solve problems of water scarcity elsewhere.

Transformations via virtual water trade will be critically important in large cities, where safe and just allocations of blue water are unlikely to be sufficient to meet minimum access needs[56] and local agricultural production is very limited. Such transformations inevitably come with inherent costs, which are likely to be incremental[57] and require strategic development in the local context[58]. Local-scale assessments can help identify suitable potential transformations that can accommodate the costs of water supply based on water availability and infrastructure costs. For example, our analysis shows that Beijing is in a catchment in the highly populous region of the North China Plain where there is insufficient surface water to meet minimum access needs while remaining within the ESB. The catchment is already outside the surface water ESB and groundwater recharge has been declining. This suggests the integration of supply side and demand side transformations would be required to live within the safe and just ESBs while meeting the needs of the population. A recent optimisation showed how a different allocation among various water sources, including local surface and groundwater, inter-basin transfers and virtual water could be used to meet the different sectors of demand in the city while minimising costs of water supply[59]. Approaches such as these can be applied with the additional constraints of the safe and just ESBs for blue water to identify avenues to meet access needs without transgressing the ESBs, however, to ensure just as well as safe outcomes, they must be grounded in principles of Earth system justice[29].

The basis of the total blue water requirement for access levels 1 and 2 is household water consumption, irrigation required for agriculture, water required for household energy production and water embodied in household infrastructure[28]. Absent from these calculations are other important water demands that are necessary to improve the income and earning capacity of countries, such as water use for agricultural exports, manufacturing and industry, and hospitals. As such, our estimates of catchments that do not have sufficient water available to meet minimum access needs and remain within the ESBs are an underestimate. Catchment-scale decision making on water use and supply must accommodate a wider array of needs such as energy production, which can involve substantial flow alteration under hydroelectric schemes[60,61] as well as treatment of poor water quality which effectively reduces water availability and impacts aquatic ecosystems. These additional human needs along with the extent to which current flow alterations have already led to a global water crisis[62] emphasise the importance of transformations to water supply and demand. Achieving the practical, catchment-scale transformations discussed here will require a dramatic shift in the way water is valued with transformations to the policy and regulatory frameworks that govern water[62].

Meeting the safe and just ESBs for all domains of the Earth system is going to be challenging and blue water offers a unique challenge given its essential nature to human survival and current inequalities in access to water. The ESBs for blue water were developed to protect the Earth system and the ecosystem services that aquatic ecosystems provide to humans. Meeting them will require radical and systemic transformations of human systems, including renegotiation of international water sharing agreements as well as education of the general public and policy makers, to ensure the basic needs for all people can be met and that there is water available for sustainable development. This is increasingly pressing given the ongoing challenges to Earth system stability including projected population growth and increasing urbanisation and the hydrological impact of climate change and subsequent impact on aquatic ecosystems. Nonetheless, it is essential to ensuring a safe and just future for all people and the planet’s blue water systems.

Methods

We have used a series of analyses to operationalise the safe and just ESBs for blue water. The first was to determine where we are already outside the ESBs for surface and groundwater. The second was to quantify whether we have sufficient surface water flows to the minimum water needs for all people to escape from poverty relying on surface water alone. The third was to quantify what proportion of groundwater recharge we would need to draw on to meet human needs while respecting the surface water ESB. The fourth was to quantify the trend in annual groundwater recharge and annual rainfall volumes.

Determining where the ESBs for surface and ground water cannot be met

We identified when a location is already outside the safe and just ESB for surface water by comparing modelled observed (altered) monthly flows with modelled pristine (unaltered) monthly flows. We calculated 20% of the long-term mean annual pristine flows at grid cells throughout global river networks as a spatially distributed volume of annual alteration that is within the safe and just ESB, leaving 80% of annual flows unaltered to protect aquatic ecosystems and the ecosystem services they provide. To quantify the extent to which river flows are outside the safe and just ESB in a given catchment, we first calculate the number of months in a year where the contemporary altered flows are more than 20% different from pristine flows using the long-term mean gridded discharge data. We then represent this data as the proportion of months in a year with more than 20% difference for each grid cell in the global river networks. For the purposes of the spatial analyses, we defined a catchment as being outside the safe and just ESB when the long-term mean observed total annual discharge at the river mouth was more than 20% different from the long-term mean pristine total annual discharge. We used total annual discharge for this analysis for comparison with the groundwater ESB, which is on an annual time step.

We identified regions that were outside the safe and just ESB for groundwater by comparing the long-term trend in groundwater storage volumes. Regions where the average annual drawdown exceeded average annual recharge showed an ongoing decline in groundwater storage and were defined as being outside the safe and just ESB for groundwater. Complementing this analysis was an analysis of the trend in annual groundwater recharge.

Quantifying whether there is sufficient surface water flows to meet minimum human needs

We compared the volume of water that was available under the safe and just ESB at the catchment scale with different volumes of water to meet human needs. We calculated total annual volumes of water required for basic human needs based on two different Minimum Access levels[28] for per capita daily water needs (Table 2, adapted from Rammelt et al.[28]). The two levels of *Domestic* access needs in Table 2 were defined according to the volume of water required to meet daily domestic needs to live a dignified life (Level 1) and to escape from poverty (Level 2). The two access levels of *All needs* represent the demand on the hydrological cycle and include the same domestic needs and the volume of water required to produce food, energy and infrastructure at the two access levels. See Rammelt et al.[28] for the full methodology used to derive these numbers.

Table 2
Minimum water needs defined by Rammelt et al.[28] to maintain a dignified life and to escape from poverty.

Water Demand Metric	Litres/capita/day	Litres/capita/year
Domestic access Level 1 (dignity)	50	18,250
Domestic access Level 2 (escape from poverty)	100	36,500
All needs access Level 1 (dignity)	292.85	106,890
All needs access Level 2 (escape from poverty)	405.67	148,069

The daily per capita water needs were converted to spatially distributed gridded annual volumes by multiplying the demand metrics by a distributed population dataset for the year 2020[63] and then summed over river basins. Long-term mean annual discharge and available surface water discharge at the basin mouth is used to define integrated water flows for the river basins. Where the annual alteration budget under the ESB for surface water was greater than the per-capita water needs for the resident population, we determined that it is possible to meet human needs from water within that catchment while meeting the ESB. Where the annual alteration allowed under the ESB was less than the per-capita water needs for the resident population, we determined that it is not possible to meet human needs from water within that catchment while meeting the ESB, creating *a safe water deficit*. For the purposes of this analysis, we made no assumptions around water storage capacity or monthly alteration levels that would be required to meet these human needs.

Quantifying what proportion of groundwater recharge is needed to meet human needs

In catchments where we cannot meet safe water needs with surface water from within the catchment, we may be able to rely on groundwater recharge to meet these needs. To quantify the extent to which groundwater recharge would be required, we converted safe water deficits for *All needs* at access level 2 to a proportion of the total annual groundwater recharge. We summed groundwater recharge volumes over river basins for these basin-level calculations. We calculated the proportion of groundwater needed to meet the safe water deficits as the ratio of the *Safe Water Deficit* and the *average annual recharge volume*.

Assessing where groundwater recharge volume is in decline

We identified pixels, and then regions, where groundwater recharge volume was in decline by quantifying the annual recharge in a given pixel and then quantifying the trend in the annual recharge. At the catchment scale, we calculated the average trend of all pixels in each catchment to define the status of whether recharge has been in decline in that catchment or not. We accompanied this with similar analyses of annual rainfall volumes to identify where declining groundwater recharge volumes is associated with declining annual rainfall.

Global surface water hydrology

We derived the pristine and disturbed monthly river flow datasets from the WBM water balance model river discharge outputs[64] at 6-minute grid cell resolution using the TerraClimate high resolution data set of monthly climate forcings[65] for the period 2000–2020. River basin delineation and flow routing configurations are defined by the WBM 6-minute topological river network used to establish local discharge and river flow[64]. The pristine and disturbed WBM runs use the same climate forcings for the 2000–2020 time period but only employ human alterations to the water cycle, including water extraction for irrigation and large reservoirs, in the disturbed runs. The modelled long-term mean contemporary global annual discharge of 38,000km^3 under this scenario is consistent with other results from the literature[66,67].

Long-term mean monthly discharge is calculated for the modelled pristine (non-human impacted) and disturbed (human impacted) discharge from the WBM model over the 2000–2020 time domain to determine the extent of altered flow. The analysis is limited to only the perennial or actively flowing river extents by applying a 3mm/yr upstream monthly average runoff exceedance threshold[68] occurring for at least 10 years out of the 2000–2020 time domain. We also mask out upstream headwater areas (smaller than 250km^2) that have modelled irrigation depths below the median irrigation depth for small headwater cells (3.6 mm/yr). This mask is applied to eliminate noise in the modelled data associated with very low irrigation and discharge values in headwater grid cells. River network and basin extents are defined by the WBM water balance model with naming convention taken from the GRDC Major River Basins of the World[69].

Global groundwater dynamics

Hydrological measurements of volumetric changes in aquifer storage are critical in assessing groundwater status but these measurements are considerably limited in several regions of the world. Given that the aquifers in some regions are typically not monitored, global scale assessments of baseline aquifer volumes are difficult. To circumvent this, the Gravity Recovery and Climate Experiment (GRACE[70]) mission has been used to track changes in several large aquifer systems around the world[71]. In this study, changes in groundwater were quantified using the GRACE data covering the period 2003–2016 (data files accessed at http://www2.csr.utexas.edu/grace/RL06_mascons.html). GRACE measures monthly changes in terrestrial water storage (TWS), being the sum of soil moisture, groundwater, surface water, snow water, and canopy storage and is expressed as:

$$TWS = SMS + GWS + SWE + SWS + CS \quad \text{Eq. 1}$$

where SMS is the soil moisture storage change, GWS is the change in groundwater storage, SWE is the change in snow water equivalent, SWS is the change in surface water storage (i.e., inland surface and reservoir storage) and CS is the water storage change in canopy. To quantify GWS, Eq. 1 was rearranged such that SMS, SWE and CS, which are model-derived outputs from the Global Land Data Assimilation

(GLDAS) NOAA Land Surface Model L4 v2.1[72] were subtracted from TWS. Outputs from hydrological (e.g., SMS, SWE, and CS) obtained from model simulations may be characterised by large uncertainties due to inadequate in-situ data for calibration and parameterization, as well as the presence of strong inter-annual and seasonal variability in surface reservoirs and snow/ice cap storage in some regions. In some regional groundwater studies, the effects of interannual changes in surface water component such as those from major lakes and reservoirs are significantly strong and have been reasonably managed and removed from the GRACE-observed TWS using data reconstruction and synthesised kernel functions[73,74]. However, a global scale groundwater processing protocol or the isolation of surface water footprint from the GRACE hydrological water column using model simulation is rather impracticable and not feasible. Alternatively, the water storage components (SMS, SWE, SWS) in Eq. 1 above have been captured in the WaterGAP Global Hydrology Model[75] and by directly subtracting these WGHM outputs from TWS will result in groundwater changes. The uncertainties in these WGHM water storage components are unknown and arguably could amplify the estimated groundwater changes from TWS, especially in regions where WGHM outputs performed poorly (e.g.,[71,74]).

To cushion the effect of such errors and uncertainties that may be propagated from this approach, much of the regions with substantial inland surface water storage changes (e.g., Caspian Sea, Black Sea, Lake Victoria, and other significant water bodies) were masked out (regions with no groundwater signal). Additionally, uncertainties caused by residual ice/snow cover from areas (e.g., Patagonia, Alaska, Himalayas, Swiss Alps, etc.) with large variations were minimised by masking such regions using the world distribution of glaciers and ice caps extents (geospatial data layer showing boundaries of such glaciers). This decision acknowledges the higher uncertainties in the simulations of these quantities by the GLDAS model. Further, some glaciers are small and may be obscured but a buffer zone of 1 arc degree was therefore created to help flag and remove such glaciers. Overall, the groundwater estimation process here is based on the water budget approach, which has been widely used in GRACE-derived groundwater storage studies (e.g., [76,77]). There are several GRACE-TWS products available from different providers, but the TWS data used in our study is a mass concentration (mascon) product (GRACE RL 06 version 02) obtained from the Center for Space Research. These mascon products are preferred to other GRACE solutions (e.g., those based on spherical harmonics) since it exhibits less signal leakage and a posteriori filtering is unnecessary as the mascon product relies on geophysical constraints to suppress noise in the data (e.g., [78]).

The estimated annual recharge volume used in this study was based on the time series of groundwater anomalies. Annual recharge was estimated by first aggregating the monthly groundwater data into annual values. Finally, for each groundwater pixel, recharge was calculated by quantifying the difference between the maximum groundwater depth in a given year and the shallowest observation of the preceding year (Fig. 5). Areas categorised as under risk of groundwater stress (i.e., groundwater in decline) were identified by computing the difference between the estimated annual recharge and draw down (also complemented by trend analysis in groundwater). Using the aggregated monthly groundwater data, the latter was quantified as the maximum groundwater values of a specific year less the observed minimum values of the following year). Notably, this draw down varies in time and space and could be human or climate driven. Accurate assessment of recharge using modelling techniques and chloride mass balance could be challenging because groundwater recharge is governed by complex interactions, including the relationship of climate change (e.g., prolonged drought) and human water abstraction with land surface conditions (e.g., increased evapotranspiration), geology and differences in water yield, among other factors. However, we found that our recharge estimates broadly aligned with some proposed estimates in the literature and other reports[79]. Moreover, the spatial distribution of trends in the time series of global groundwater and annual recharge were estimated using the least squares approach.

Trends in annual rainfall volume

The trends (mm/yr) in annual rainfall were based on monthly Global Precipitation Climatology Centre (GPCC) precipitation data (mm). The GPCC-based precipitation is one of the widely used gridded rainfall products because it consists of quality-controlled observational data from 67,200 gauged stations world-wide[80]. The GPCC data is available on a 0.25° spatial resolution and was accessed from NOAA’s repository (https://psl.noaa.gov/data/gridded/data.gpcc.html). The monthly grids (spatial and temporal dimensions) of GPCC rainfall were generated from the scientific file format (popularly called Network Common Data Form) and accumulated to annual values using scripts written in Matlab R2018A version, underpinned by the Mapping and Aerospace Tool boxes. The least squares approach was then used to estimate the trends in the time series of the annual rainfall data for the period between 2002 and 2016, consistent with other data used in this study.

Declarations

Acknowledgements

The Earth Commission is hosted by Future Earth and is the science component of the Global Commons Alliance. The Global Commons Alliance is a sponsored project of Rockefeller Philanthropy Advisors, with support from Oak Foundation, MAVA, Porticus, Gordon and Betty Moore Foundation, Tiina and Antti Herlin Foundation, William and Flora Hewlett Foundation, and the Global Environment Facility. The Earth Commission is also supported by the Global Challenges Foundation. The funders had no role in study design, data collection and analysis, decision to publish or preparation of the manuscript.

Author contributions

All authors contributed to the work presented in this paper. BSK, SEB, PG and CN jointly designed and implemented the methods. BSK drafted the main paper and BSK, PG and CN wrote the Methodology. All other authors provided conceptual advice, discussed the results and implications, and commented extensively on the manuscript at all stages. BSK, PG and CN produced the figures.

References

1. Vörösmarty, C.J., et al. Global water, the anthropocene and the transformation of a science. *COSUST* **5**, 539-550 https://doi.org/10.1016/j.cosust.2013.10.005 (2013).
2. Falkenmark, M., Wang-Erlandsson, L. & Rockström, J. Understanding of water resilience in the Anthropocene. *J. Hydrol.* X **2**, 100009 https://doi.org/10.1016/j.hydroa.2018.100009 (2019).
3. Scanlon, B.R., et al. Global water resources and the role of groundwater in a resilient water future. *Nature Reviews Earth & Env.***4**, 87-101 https://doi.org/10.1038/s43017-022-00378-6 (2023).
4. Lytle, D.A. & Poff, N.L. Adaptation to natural flow regimes. *Trends Ecol. Evol*. **19**, 94-100 https://doi.org/10.1016/j.tree.2003.10.002(2004).
5. Rinke, K., et al. Ecosystem Services from Inland Waters and Their Aquatic Ecosystems, in *Atlas of Ecosystem Services: Drivers, Risks, and Societal Responses*, M. Schröter, et al., Editors., Springer International Publishing: Cham. 191-195. https://doi.org/10.1007/978-3-319-96229-0_30 (2019).
6. Vörösmarty, C.J., et al. A green-gray path to global water security and sustainable infrastructure. *Global Env. Change***70**, 102344. https://doi.org/10.1016/j.gloenvcha.2021.102344 (2021).
7. Mitsch, W.J. & Gosselink, J.G. *Wetlands*.: John Wiley & Sons. https://www.wiley.com/en-us/Wetlands,+5th+Edition-p-9781118676820 (2015).
8. Bimrah, K., Dasgupta, R. & Saizen, I. Cultural Ecosystem Services of Mangroves: A Review of Models and Methods, in *Assessing, Mapping and Modelling of Mangrove Ecosystem Services in the Asia-Pacific Region*, R. Dasgupta, S. Hashimoto, and O. Saito, Editors. Springer Nature Singapore: Singapore. 239-250. https://doi.org/10.1007/978-981-19-2738-6_13 (2022).
9. McIntyre, P.B., Reidy Liermann, C.A. & Revenga, C. Linking freshwater fishery management to global food security and biodiversity conservation. *PNAS* **113**, 12880-12885. https://doi.org/10.1073/pnas.1521540113 (2016).
10. Lynch, A.J., et al. The social, economic, and environmental importance of inland fish and fisheries. *Env. Rev.***24**, 115-121. https://cdnsciencepub.com/doi/full/10.1139/er-2015-0064 (2016).
11. Broadley, A., et al. A global review of the critical link between river flows and productivity in marine fisheries. *Rev. Fish Biol. Fisheries***32**, 805-825. https://doi.org/10.1007/s11160-022-09711-0 (2022).
12. Poff, N.L. & Zimmerman, J.K.H. Ecological responses to altered flow regimes: a literature review to inform the science and management of environmental flows. *Freshw. Biol.***55**, 194-205. https://doi.org/10.1111/j.1365-2427.2009.02272.x (2010).
13. Webb, A.J., et al. Squeezing the most out of existing literature: a systematic re-analysis of published evidence on ecological responses to altered flows. *Freshw. Biol.***58**, 2439-2451. https://doi.org/10.1111/fwb.12234 (2013).
14. Borgwardt, F., et al. Exploring variability in environmental impact risk from human activities across aquatic ecosystems. *Sci. Total Environ.***652**, 1396-1408. https://doi.org/10.1016/j.scitotenv.2018.10.339 (2019).

15. Famiglietti, J.S. The global groundwater crisis. *Nature Climate Change* **4**, 945-948. https://doi.org/10.1038/nclimate2425 (2014).
16. de Graaf, I.E.M., et al. Environmental flow limits to global groundwater pumping. *Nature* **574**, 90-94. https://doi.org/10.1038/s41586-019-1594-4 (2019).
17. Gleeson, T., et al. Global Groundwater Sustainability, Resources, and Systems in the Anthropocene. *Annu. Rev. Earth Planet. Sci.* **48**, 431-463. https://doi.org/10.1146/annurev-earth-071719055251 (2020).
18. Basack, S., et al. Saltwater Intrusion into Coastal Aquifers and Associated Risk Management: Critical Review and Research Directives. *J. Coast. Res.* **38**, 654-672. https://doi.org/10.2112/JCOASTRES-D-21-00116.1 (2022).
19. Mukherjee, A., et al. Chapter 1 - Global groundwater: from scarcity to security through sustainability and solutions, in *Global Groundwater*, A. Mukherjee, et al., Editors. Elsevier. p. 3-20. https://doi.org/10.1016/B978-0-12-818172-0.00001-3 (2021).
20. Naiman, R.J. & Dudgeon, D. Global alteration of freshwaters: influences on human and environmental well-being. *Ecol. Res.* **26**, 865-873. https://doi.org/10.1007/s11284-010-0693-3 (2011).
21. Pradhan, A. & Srinivasan, V. Do dams improve water security in India? A review of post facto assessments. *Water Security* **15**,100112. https://doi.org/10.1016/j.wasec.2022.100112 (2022).
22. Rockström, J., et al. A safe operating space for humanity. *Nature* **461**, 472-475. https://www.nature.com/articles/461472a (2009).
23. Steffen, W., et al. Planetary boundaries: Guiding human development on a changing planet. *Science* **347**, 1259855. https://www.science.org/doi/full/10.1126/science.1259855 (2015).
24. Gerten, D., et al. Towards a revised planetary boundary for consumptive freshwater use: role of environmental flow requirements. *COSUST* **5**, 551-558. https://www.sciencedirect.com/science/article/pii/S1877343513001498 (2013).
25. Wang-Erlandsson, L., et al. A planetary boundary for green water. *Nature Reviews Earth & Environment* **3**, 380-392. https://www.nature.com/articles/s43017-022-00287-8 (2022).
26. Rockström, J., et al. Why we need a new economics of water as a common good. *Nature* **615**,794-797.https://www.nature.com/articles/d41586-023-00800-z (2023).
27. Rockström, J. et al. Safe and just Earth system boundaries. *Nature* (accepted 14/04/2023).
28. Rammelt, C.F., et al. Impacts of meeting minimum access on critical earth systems amidst the Great Inequality. *Nature Sustainability* **6**, 212-221. https://doi.org/10.1038/s41893-022-00995-5 (2023).
29. Gupta, J., et al. Earth system justice needed to identify and live within Earth system boundaries. *Nature Sustainability* https://doi.org/10.1038/s41893-023-01064-1 (2023).
30. Arthington, A.H., et al. The Brisbane Declaration and Global Action Agenda on Environmental Flows (2018). *Front. Environ. Sci.* **6**. https://doi.org/10.3389/fenvs.2018.00045 (2018).
31. Richter, B.D., et al. A presumptive standard for environmental flow protection. *Riv. Res. Appl.* **28**, 1312-1321. https://doi.org/10.1002/rra.1511 (2012).

32. van Vliet, M.T.H., et al. Global water scarcity including surface water quality and expansions of clean water technologies. *Environ. Res. Lett.* **16**, 024020. https://doi.org/10.1088/1748-9326/abbfc3 (2021).
33. Misra, A.K. Climate change and challenges of water and food security. *Int. J. Sustain. Built Environ.***3**, 153-165. https://doi.org/10.1016/j.ijsbe.2014.04.006 (2014).
34. O'Brien, K. Is the 1.5°C target possible? Exploring the three spheres of transformation. *COSUST***31**, 153-160. https://doi.org/10.1016/j.cosust.2018.04.010 (2018).
35. Gupta, J. & Lebel, L. Access and allocation in earth system governance: lessons learnt in the context of the Sustainable Development Goals. *Int. Environ. Agreem.: Politics Law Econ.***20**, 393-410. https://doi.org/10.1007/s10784-020-09486-4 (2020).
36. Howard, G., et al. *Domestic water quantity, service level and health*. World Health Organization, (2https://apps.who.int/iris/bitstream/handle/10665/338044/9789240015241-eng.pdf (2020).
37. Poore, J. & Nemecek, T. Reducing food's environmental impacts through producers and consumers. *Science***360**, 987-992. https://doi.org/10.1126/science.aaq0216 (2018).
38. Molden, D.E. *Water for Food Water for Life: A Comprehensive Assessment of Water Management in Agriculture* (1st ed.). Routledge. https://doi.org/10.4324/9781849773799 (2007).
39. Puy, A., et al. The delusive accuracy of global irrigation water withdrawal estimates. *Nature Communications* **13**, 3183. https://doi.org/10.1038/s41467-022-30731-8 (2022).
40. Grafton, R.Q., et al. The paradox of irrigation efficiency. *Science***361**, 748-750. https://doi.org/10.1126/science.aat9314 (2018).
41. Jägermeyr, J., et al. Water savings potentials of irrigation systems: global simulation of processes and linkages. *Hydrol. Earth Syst. Sci.***19**, 3073-3091. https://doi.org/10.5194/hess-19-3073-2015 (2015).
42. Turner, S.W.D., et al. Influence of Groundwater Extraction Costs and Resource Depletion Limits on Simulated Global Nonrenewable Water Withdrawals Over the Twenty-First Century. *Earth's Future***7**, 123-135. https://doi.org/10.1029/2018EF001105 (2019).
43. Bosch, H.J. & Gupta, J. Water property rights in investor-state contracts on extractive activities, affects water governance: An empirical assessment of 80 contracts in Africa and Asia. *Rev. Eur. Comp. Int. Environ. Law***31**, 295-316. https://onlinelibrary.wiley.com/doi/full/10.1111/reel.12436 (2022).
44. Döll, P., et al. Impact of water withdrawals from groundwater and surface water on continental water storage variations. *J. Geodyn.***59-60**, 143-156. https://doi.org/10.1016/j.jog.2011.05.001 (2012).
45. Gleeson, T. & Richter, B. How much groundwater can we pump and protect environmental flows through time? Presumptive standards for conjunctive management of aquifers and rivers. *Riv. Res. Appl.***34**, 83-92. https://doi.org/10.1002/rra.3185 (2018).
46. d'Odorico, P., et al. Global virtual water trade and the hydrological cycle: patterns, drivers, and socio-environmental impacts. *Environ. Res. Lett.* **14**, 053001. https://doi.org/10.1088/1748-9326/ab05f4 (2019).

47. Sun, J.X., et al. Review on research status of virtual water: The perspective of accounting methods, impact assessment and limitations. *Agric. Water Manag.***243**, 106407. https://doi.org/10.1016/j.agwat.2020.106407 (2021).
48. Porkka, M., et al. The use of food imports to overcome local limits to growth. *Earth's Future***5**, 393-407. https://doi.org/10.1002/2016EF000477 (2017).
49. Hoekstra, A.Y. & Hung, P.Q. Globalisation of water resources: international virtual water flows in relation to crop trade. *Glob. Environ. Change* **15**, 45-56. https://doi.org/10.1016/j.gloenvcha.2004.06.004 (2005).
50. Hoekstra, A.Y. & Mekonnen, M.M. The water footprint of humanity. *PNAS* **109**, 3232-3237. https://doi.org/10.1073/pnas.1109936109 (2012).
51. Wu, X.D., et al. Global socio-hydrology: An overview of virtual water use by the world economy from source of exploitation to sink of final consumption. *J. Hydrol.***573**, 794-810. https://doi.org/10.1016/j.jhydrol.2019.03.080 (2019).
52. Rosa, L., et al. Global unsustainable virtual water flows in agricultural trade. Environmental Research Letters, 2019. 14(11): p. 114001. https://doi.org/10.1088/1748-9326/ab4bfc
53. Konar, M., et al. The water footprint of staple crop trade under climate and policy scenarios. *Environ. Res. Lett*. **11**, 035006. http://dx.doi.org/10.1088/1748-9326/11/3/035006 (2016).
54. Liu, W., et al. Water resources conservation and nitrogen pollution reduction under global food trade and agricultural intensification. *Sci. Total Environ.***633**, 1591-1601. https://doi.org/10.1016/j.scitotenv.2018.03.306 (2018).
55. Rosa, L., et al. Closing the yield gap while ensuring water sustainability. *Environ. Res. Lett*. **13**, 104002. https://doi.org/10.1088/1748-9326/aadeef (2018).
56. Bai, X., et al. How to stop cities and companies causing planetary harm. *Nature***609**, 463-466. https://doi.org/10.1038/d41586-022-02894-3 (2022).
57. Marlow, D.R., et al. Towards sustainable urban water management: A critical reassessment. *Water Res.***47**, 7150-7161. https://doi.org/10.1016/j.watres.2013.07.046 (2013).
58. Ferguson, B.C., Frantzeskaki, N. & Brown, R.R. A strategic program for transitioning to a Water Sensitive City. *Landsc. Urban Plan*. **117**,32-45. https://doi.org/10.1016/j.landurbplan.2013.04.016 (2013).
59. Ye, Q., et al. Optimal allocation of physical water resources integrated with virtual water trade in water scarce regions: A case study for Beijing, China. *Water Res.***129**, 264-276. https://doi.org/10.1016/j.watres.2017.11.036 (2018).
60. Winemiller, K.O., et al. Balancing hydropower and biodiversity in the Amazon, Congo, and Mekong. *Science*, **351**, 128-129. https://doi.org/10.1126/science.aac7082 (2016).
61. Arantes, C.C., et al. Impacts of hydroelectric dams on fishes and fisheries in tropical rivers through the lens of functional traits. *COSUST* **37**, 28-40. https://doi.org/10.1016/j.cosust.2019.04.009 (2019).

62. GCEW. *The What, Why and How of the World Water Crisis: Global Commission on the Economics of Water Phase 1 Review and Findings*. Global Commission on the Economics of Water: Paris. https://watercommission.org/wp-content/uploads/2023/03/Why-What-How-of-Water-Crisis-Web.pdf (2023).
63. Center for International Earth Science Information Network, C.C.U. Gridded Population of the World, Version 4 (GPWv4): Population Density, Revision 11. NASA Socioeconomic Data and Applications Center (SEDAC): Palisades, New York. https://doi.org/10.7927/H49C6VHW (2018).
64. Wisser, D., et al. Reconstructing 20th century global hydrography: a contribution to the Global Terrestrial Network- Hydrology (GTN-H). *Hydrol. Earth Syst. Sci.***14**, 1-24. https://doi.org/10.5194/hess-14-1-2010 (2010).
65. Abatzoglou, J.T., et al. TerraClimate, a high-resolution global dataset of monthly climate and climatic water balance from 1958–2015. *Sci. Data***5**, 170191. https://doi.org/10.1038/sdata.2017.191 (2018).
66. Zhang, Y., et al. A Climate Data Record (CDR) for the global terrestrial water budget: 1984–2010. *Hydrol. Earth Syst. Sci.***22**, 241-263. https://doi.org/10.5194/hess-22-241-2018 (2018).
67. Recknagel, T., et al. Global Freshwater Fluxes into the World Oceans. in EGU General Assembly Conference Abstracts. https://www.kliwas.de/DE/05_Wissen/04_Pub/02_Mitteilungen/BfG-Mitteilungen36.html?nn=174586 (2021).
68. Fekete, B.M., Vörösmarty, C.J. & Lammers, R.B. Scaling gridded river networks for macroscale hydrology: Development, analysis, and control of error. *Water Resour. Res.***37**, 1955-1967. https://doi.org/10.1029/2001WR900024 (2001).
69. GRDC. *Major River Basins of the World*. Federal Institute of Hydrology (BfG). Koblenz, Germany. https://www.bafg.de/GRDC/EN/02_srvcs/22_gslrs/221_MRB/riverbasins.html (2020).
70. Tapley, B.D., et al. GRACE Measurements of Mass Variability in the Earth System. *Science***305**, 503-505. https://doi.org/10.1126/science.1099192 (2004).
71. Chen, J., et al. Groundwater Storage Changes: Present Status from GRACE Observations, in *Remote Sensing and Water Resources*, A. Cazenave, et al., Editors. Springer International Publishing: Cham. 207-227. https://link.springer.com/chapter/10.1007/978-3-319-32449-4_9 (2016).
72. Beaudoing, H.a.M.R. *NASA/GSFC/HSL GLDAS Noah Land Surface Model L4 3 hourly 0.25 x 0.25 degree V2.1* Goddard Earth Sciences Data and Information Services Center (GES DISC): Greenbelt, Maryland, USA. https://disc.gsfc.nasa.gov/datasets/GLDAS_NOAH025_3H_2.1/summary (2020).
73. Ferreira, V.G., et al. Characterization of the hydro-geological regime of Yangtze River basin using remotely-sensed and modeled products. *Sci. Total Environ.***718**, 137354. https://doi.org/10.1016/j.scitotenv.2020.137354 (2020).
74. Agutu, N.O., et al. GRACE-derived groundwater changes over Greater Horn of Africa: Temporal variability and the potential for irrigated agriculture. *Sci. Total Environ.***693**, 133467. https://www.sciencedirect.com/science/article/pii/S004896971933387X (2019).

75. Döll, P., Kaspar, F. & Lehner, B. A global hydrological model for deriving water availability indicators: model tuning and validation. *J. Hydrol.***270**, 105-134. https://doi.org/10.1016/S0022-1694(02)00283-4 (2003).
76. Ojha, C., Werth, S. & Shirzaei, M. Groundwater Loss and Aquifer System Compaction in San Joaquin Valley During 2012–2015 Drought. *J. Geophys. Res. Solid Earth* **124**, 3127-3143. https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2018JB016083 (2019).
77. Thomas, B.F. & Famiglietti, J.S. Identifying Climate-Induced Groundwater Depletion in GRACE Observations. *Sci. Rep.***9**,4124. https://www.nature.com/articles/s41598-019-40155-y (2019).
78. Watkins, M.M., et al. Improved methods for observing Earth's time variable mass distribution with GRACE using spherical cap mascons. *J. Geophys. Res. Solid Earth* **120**, 2648-2671. https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2014JB011547 (2015).
79. Moeck, C., et al. A global-scale dataset of direct natural groundwater recharge rates: A review of variables, processes and relationships. *Sci. Total Environ.***717**, 137042. https://doi.org/10.1016/j.scitotenv.2020.137042 (2020).
80. Schneider, U., et al. GPCC's new land surface precipitation climatology based on quality-controlled in situ data and its role in quantifying the global water cycle. *Theor. Appl. Climatol.***115**, 15-40. https://doi.org/10.5676/DWD_GPCC/FD_M_V7_050 (2014).

Figures

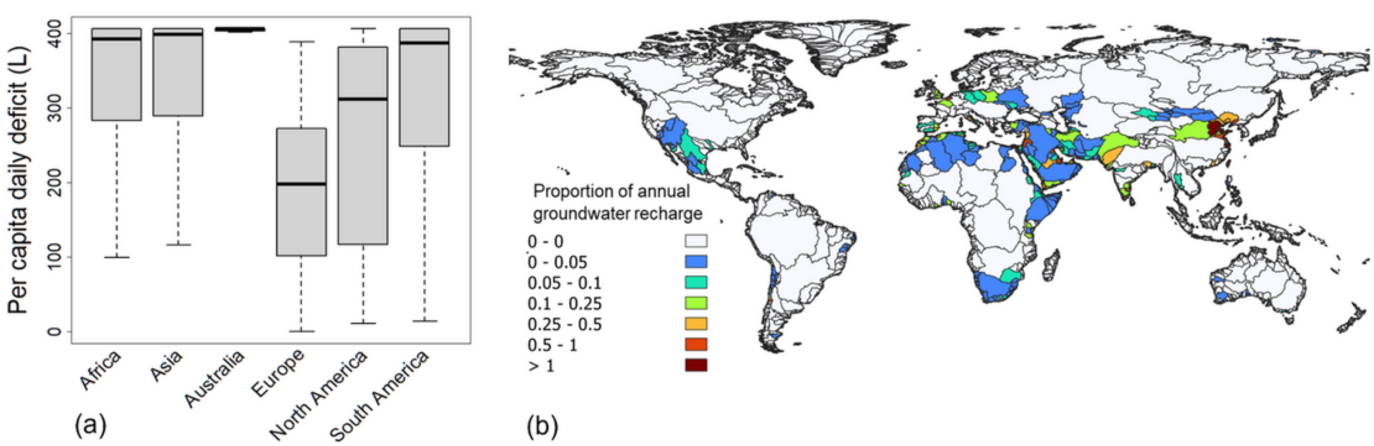

Figure 1

a) The distribution of daily per capita deficits for all water needs Level 2 in each continent for catchments where these needs cannot be met by surface water flows alone; **b)** the proportion of groundwater recharge that would be required to meet that deficit in each catchment. Catchments with no shading in b) are those where there should be sufficient surface water to meet all needs at access level 2 (406 litres person^{-1} day^{-1}).

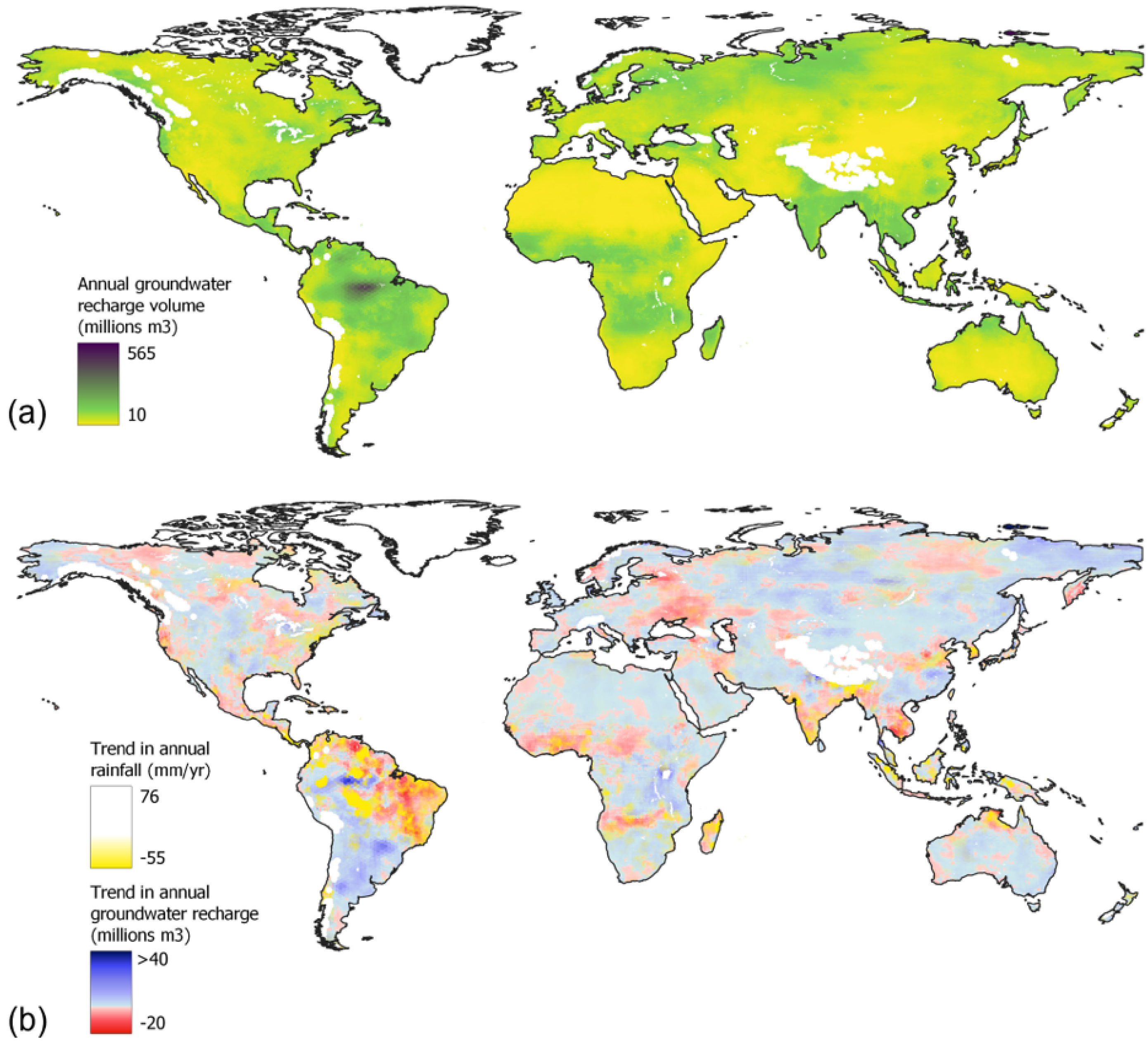

Figure 2

a) Average annual groundwater recharge volume derived from GRACE (Tapley et al., 2004), representing the safe and just volume of groundwater that can be drawn down annually (including natural groundwater discharge and anthropogenic extraction). **b)** The trend in annual recharge volume between 2003-2016, showing where annual recharge is declining (hotter colours) or increasing (cooler colours). Yellow shading in b) shows where there has been an associated decline in annual rainfall.

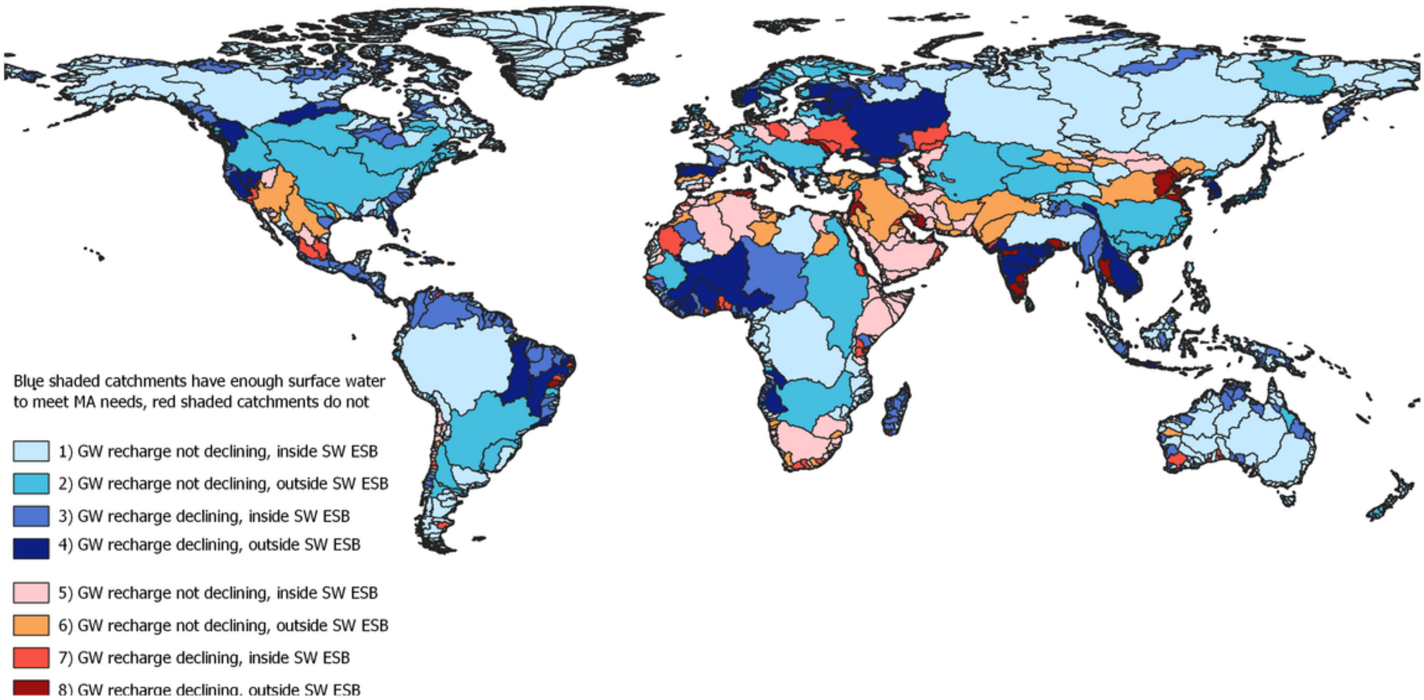

Figure 3

The eight groups of river catchments as defined by their status of surface and groundwater with respect to the safe and just ESBs (see also Fig. 4).

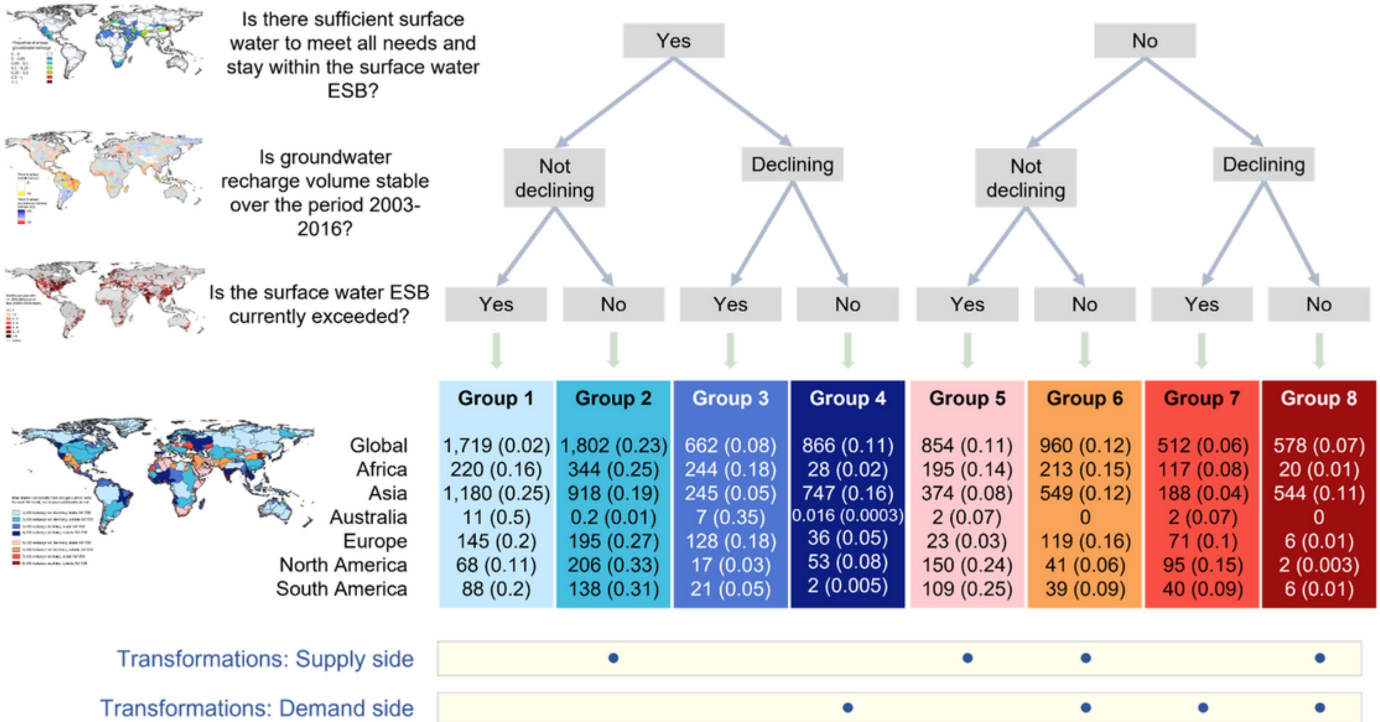

Figure 4

Populations living in different catchments, classified according to i) whether there should be sufficient (unaltered) surface water flows to meet all needs at access Level 2, ii) whether groundwater recharge is stable or has been declining over the period of record and iii) whether we are inside or outside the surface water ESB on an annual basis based on current surface water flows (Fig. S1a). Populations are estimated globally and by continent. Population numbers are in millions and numbers in parentheses show the proportion of the total population, globally and within each continent, in each group. Blue dots indicate the type of transformations that are likely required to meet minimum access needs while meeting the safe and just ESBs.

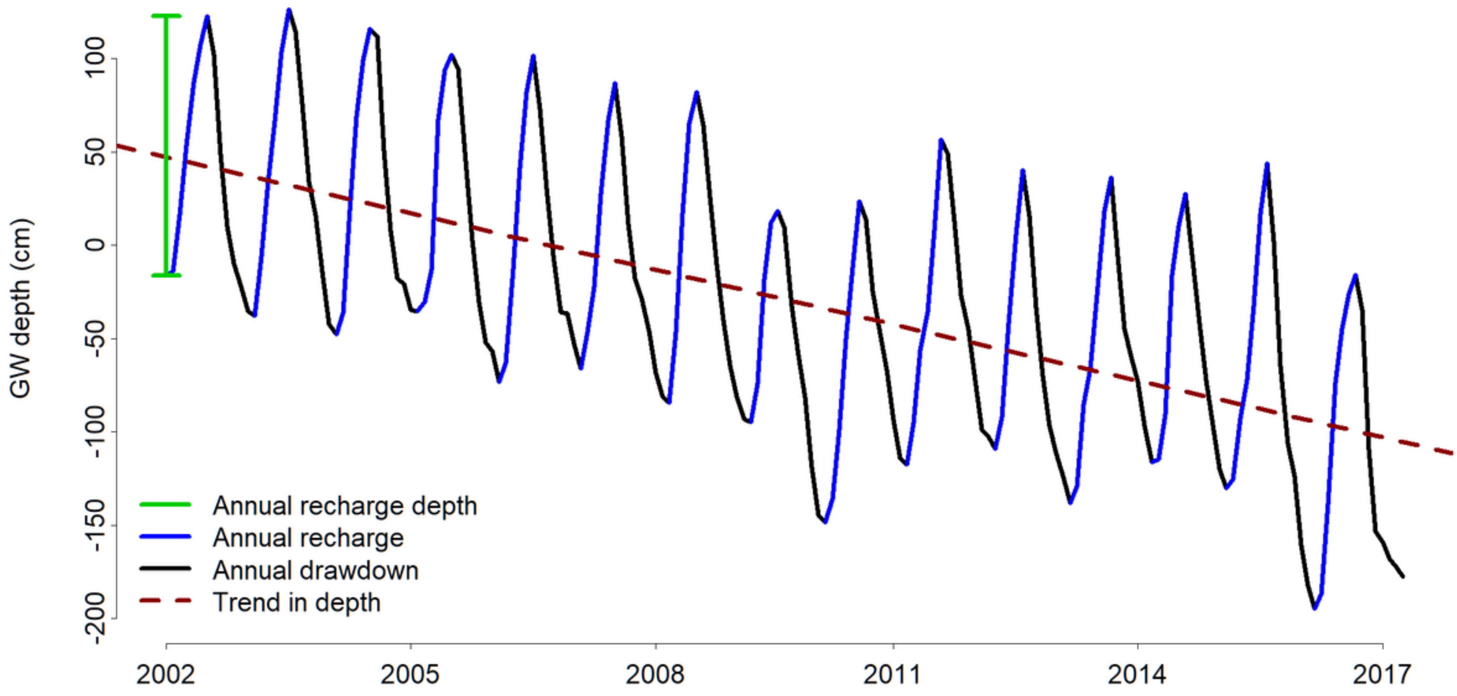

Figure 5

Time series of monthly groundwater depth showing the annual recharge and drawdown cycle. The safe and just ESB for groundwater drawdown is the long-term average annual recharge depth, converted to a volume. Annual groundwater recharge is shown by the blue lines in the time series with the first annual recharge also illustrated by the green vertical line. Long-term declines in groundwater depth occur when the long-term annual drawdown exceeds the long-term annual recharge. When this occurs from declines in annual recharge, potentially due to climatic variability, the safe and just ESB will begin to shrink

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- SupplementaryInformation.docx